Sustainable Vibration Energy Harvesting Based on Zr-Doped PMN-PT Piezoelectric Single Crystal Cantilevers

Seung Eon Moon, Sung Q Lee, Sang-kyun Lee, Young-Gi Lee, Yil Suk Yang, Kang-Ho Park, and Jongdae Kim

In this paper, we present the results of a preliminary study on the piezoelectric energy harvesting performance of a Zr-doped $PbMg_{1/3}Nb_{2/3}O_3$-$PbTiO_3$ (PMN-PZT) single crystal beam. A novel piezoelectric beam cantilever structure is used to demonstrate the feasibility of generating AC voltage during a state of vibration. The energy-harvesting capability of a PMN-PZT beam is calculated and tested. The frequency response of the cantilever device shows that the first mode resonance frequency of the excitation model exists in the neighborhood of several hundreds of hertz, which is similar to the calculated value. These tests show that several significantly open AC voltages and sub-mW power are achieved. To test the possibility of a small scale power source for a ubiquitous sensor network service, energy conversion and the testing of storage experiment are also carried out.

Keywords: Vibration energy harvesting, PMN-PZT, piezoelectric, cantilever.

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I. Introduction

With the recent progress of mobile technologies and remote sensing systems, ubiquitous sensor networks (USNs) have been of great interest due to their potential to create a large market and their significant impact on human life [1]-[3]. In realizing various USN services, one of the main problems yet to be solved is the finite power sources of batteries in sensor nodes. Fixed energy sources such as batteries and fuel cells have serious drawbacks such as bulkiness with a finite amount of energy, limited lifetime, and use of hazardous chemicals that require periodic recharging or replacement. Therefore, many researchers have been studying the scavenging of energy from the environment. There are several power-generating methods using ambient environmental energy, including thermal gradients, solar energy, and vibration energy [4]-[9]. Among these, to drive an electromechanical converter from ambient motion or vibration has some advantages, for example, independence of light intensity, various vibration sources, and so on. The piezoelectric energy harvested from ambient vibration sources has attracted a great deal of attention because of its high power density, lack of power source necessity, and controllability of the output voltage compared to other vibration energy scavenging methods such as electromagnetic and electrostatic methods.

Converting an environmental mechanical vibration into electrical energy has been actively explored using various piezoelectric materials and designs. To enhance mechanical-to-electrical energy conversion, several considerations have been proposed to improve the conversion efficiency in piezoelectric energy harvesting devices. Besides matching a natural resonance frequency with that of an environmental vibration source and the uniform distribution of the strain/stress on the piezoelectric material due to the vibration, a high conversion material (high $d \times g$, d: piezoelectric strain constant, g: piezoelectric voltage constant) is needed. Proper modeling would also be helpful to make a reproducible piezoelectric energy-harvesting device.

Recently, numerous attempts have been made to increase the efficiency of piezoelectric energy-harvesting devices with new piezoelectric materials and innovative electrode designs, resulting in the development of several bulk piezoelectric energy generators [10], [11]. Various equivalent models and circuits have also been proposed [12]-[21]

In this study, to increase the generating power, we report on the performance of a piezoelectric energy-harvesting device with a Zr-doped $PbMg_{1/3}Nb_{2/3}O_3$-$PbTiO_3$ (PMN-PZT) piezoelectric single crystal having a higher piezoelectric strain constant d and a higher piezoelectric voltage constant g than conventional piezoelectric materials. To acquire a reliable piezoelectric energy-harvesting device, proper modeling was adapted to the measured results.

II. Fabrication and Measurements

Zr-doped PMN-PT single-crystal relaxor ferroelectric material was used for the piezoelectric cantilever structure, which has piezoelectric constants about five times larger than those of conventional piezoelectric ceramics. The piezoelectric single crystal PMN-PZT samples (25 mm×5 mm×0.25 mm) used here have an EM coupling factor of 0.91 and a piezoelectric constant of 1850 pC/N, according to the manufacturer (CPSC160-95), which are considerably larger values than in other piezoelectric materials in commercial products [22].

A cantilever-type device was chosen among the many power-generating structures because of a larger displacement which induces a larger strain/stress in the piezoelectric materials during the same vibration. A piezoelectric energy-harvesting device consists of a PMN-PZT single-crystal beam bonded to an FR4 substrate of 0.55 mm thickness with the same size. For the PMN-PZT single-crystal beam, a gold electrode was coated on both sides and electrically poled sufficiently. Figure 1(a) shows the cantilever-type piezoelectric energy-harvesting device standing on a PCB jig. The output wires were connected on both electrodes using silver paste and epoxy glue. One end of the device was clamped to a shaker as a cantilever with an overhanging length of about 20 mm.

The electrical properties of the fabricated devices were measured using an Agilent 4194A, an Agilent 35670A, a digital oscilloscope, and a probe station. The frequency-dependent

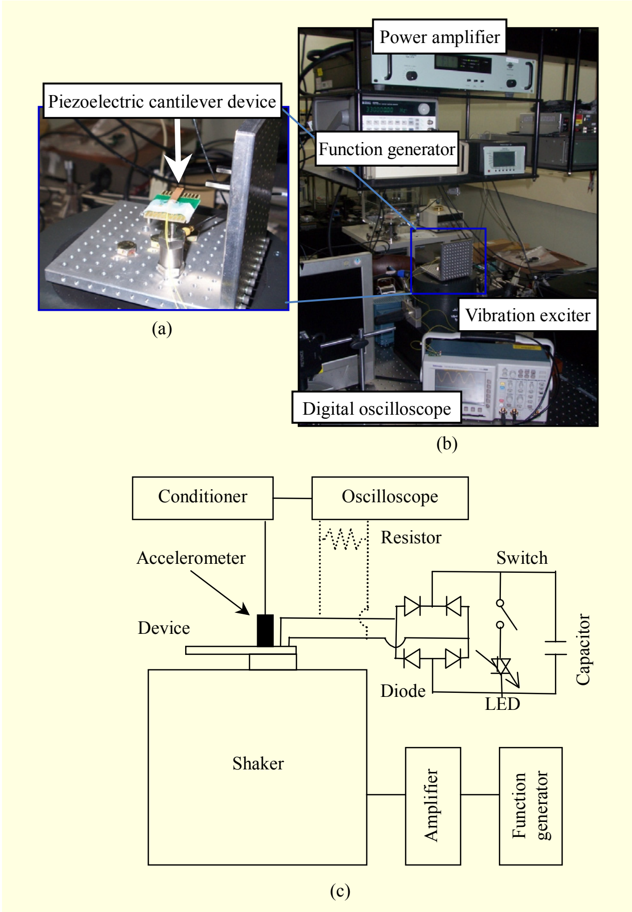

Fig. 1. (a) Cantilever-type piezoelectric energy harvesting device standing on a PCB jig, (b) experimental setup, and (c) schematic diagram for measuring the performances of the piezoelectric energy harvesting device.

impedance/phase angle, capacitance/quality factor values, FFT spectrum, and mechanical damping ratio were measured.

The experimental set-up and schematic diagram for measuring the performance of the piezoelectric energy-harvesting device are shown in Figs. 1(b) and (c), respectively. A vibration exciter (B&K, Type 4808) was used to supply reliable mechanical vibrations to the device. The shaker was controlled by an HP 33120A function generator and power amplifier (B&K, Type 2719). The accelerometer sensor was located under the base of the PCB jig and used to measure the acceleration of the device. The measured acceleration from the sensor and the output voltage of the device were displayed on the oscilloscope (Tektronix, TDS3012B).

The output power generated by the piezoelectric energy-harvesting device is determined using the measured voltage across the load resistor connected to the device; the peak power P can be defined as $P = \left(\frac{V_{pp}}{2}\right)^2 / R$, $P = \left(\frac{V_{pp}}{2}\right)^2$, where V_{pp} is the measured peak-to-peak AC voltage generated by the device, and R is the load resistance.

To test the possibility of energy conversion and conduct a storage experiment, an electrical circuit made up of a rectifying diode, resistor, capacitor, LED, and switch was created. The rectifier circuit consists of 4 diodes (1N4148) in the form of a full bridge. After rectifying, the output power flows through an LED and its load resistor (220 Ω) in order to verify the power generation. The output power can be switched to a storage part that is made of a 1 μF capacitor as shown in Fig. 1(c). The circuit has a storage (capacitor) mode and power consumption mode (LED) that can be manually selected through a switch.

III. Results and Discussion

The impedance and phase angle versus frequency of the PMN-PZT/FR4 cantilever device, measured using an impedance analyzer, are shown in Fig. 2(a). The resonance and anti-resonance frequency characteristics of the impedance and phase of the device at 25°C are shown. Note that off of resonance, the cantilever was a capacitor exhibiting a phase angle of around -90°. At resonance, the flexural motion gave

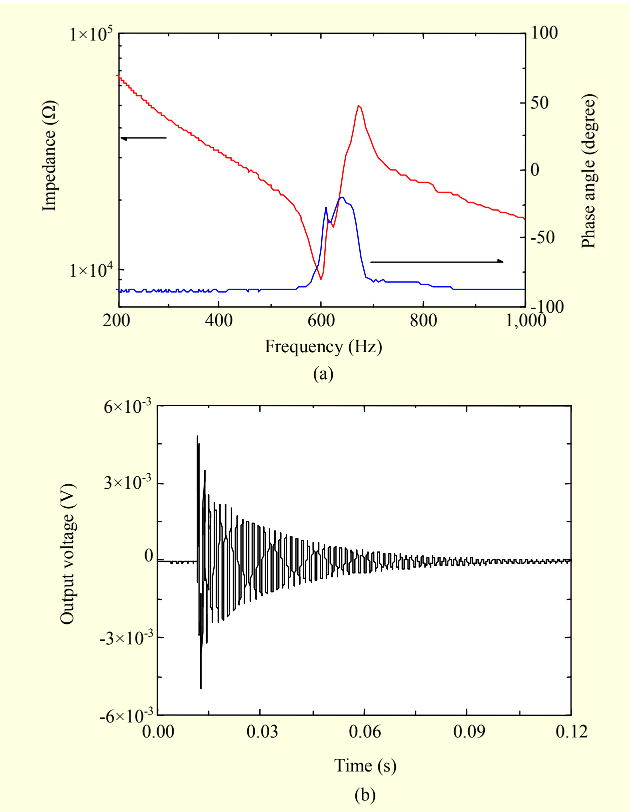

Fig. 2. (a) Measured impedance and phase angle versus frequency and (b) damped oscillation from a force impulse of a PMN-PZT/FR4 cantilever device.

rise to a peak in the real part of the impedance and hence a peak in the phase angle due to the direct piezoelectric effect.

The flexural resonance frequency f_n of the cantilever structure is related to the bending modulus per unit width, the length, and the mass per unit area of the cantilever, as $f_n = \frac{v_n^2}{2\pi}\frac{1}{L^2}\sqrt{\frac{D_p}{m}}$, where v_n^2 is a dimensionless n-th-mode eigenvalue; L is the cantilever length; D_p is the bending modulus, which is a function of Young's modulus and the thickness of the constituents; and m is the mass per unit area of the cantilever, which is a function of the density and thickness of the constituents [23]. As can be seen from Fig. 2, the first bending-mode resonance appeared at about 630 Hz. The calculated value using the measured dimensions and the above equation is about 430 Hz. This discrepancy is attributed mainly to the simplifications of the model, ignoring other thinner layers and assuming perfect adhesion between layers.

A quick observation of the measurement of an output voltage utilizing the application of a vibration step is shown in Fig. 2(b). Comparing the amplitude of successive amplitude peaks, Vi, of the output voltage, the calculated mechanical damping ratio is about 0.03.

The natural frequency of the device was sought using a frequency sweeping process. The device was excited under a resonant frequency with accelerations of 0.5 g_{rms} and 1 g_{rms}. The measured acceleration waveform in the accelerometer sensor and the AC output of the device from this acceleration in an oscilloscope are shown in Fig. 3(a). Because the applied waveform was a sine wave and the sensitivity of the accelerometer sensor was 100 mV/g, the acceleration waveform was also a sine wave and the RMS value in the acceleration amplitude of the device was 100 mV. In this way, the acceleration in the device was maintained at 0.5 g_{rms} or 1 g_{rms} by controlling the amplitude of the applied waveform.

The AC output of the device is maximized when its natural frequency matches the frequency of the vibration source. Generally, the AC output of the device shows a frequency-dependant symmetric shape as shown in Fig. 3(b). In the figure, the AC output voltages are linearly proportional to the applied acceleration. The mechanical quality factor Q of the cantilever device, which can be defined as the center frequency divided by the 3 dB frequency width of the output voltage, is estimated at about 35 for 0.5 g_{rms} and 1 g_{rms} acceleration. A high Q-factor means low energy loss, which is good for an energy converter; however, a little deviation of the vibration frequency from the device's resonant frequency will induce tremendous reduction of output power.

To measure the output power of the piezoelectric energy-harvesting device, the AC output voltage was measured for the

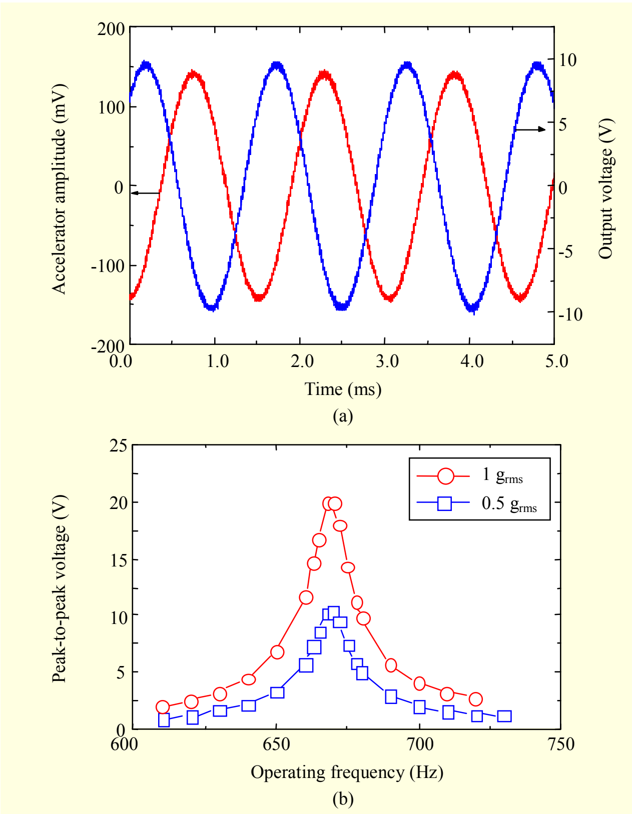

Fig. 3. (a) Measured acceleration waveform in an accelerometer sensor and the output AC voltage of the device for 1 g acceleration in an oscilloscope and (b) AC output voltage versus frequency of the device for 0.5 g_{rms} and 1 g_{rms} acceleration.

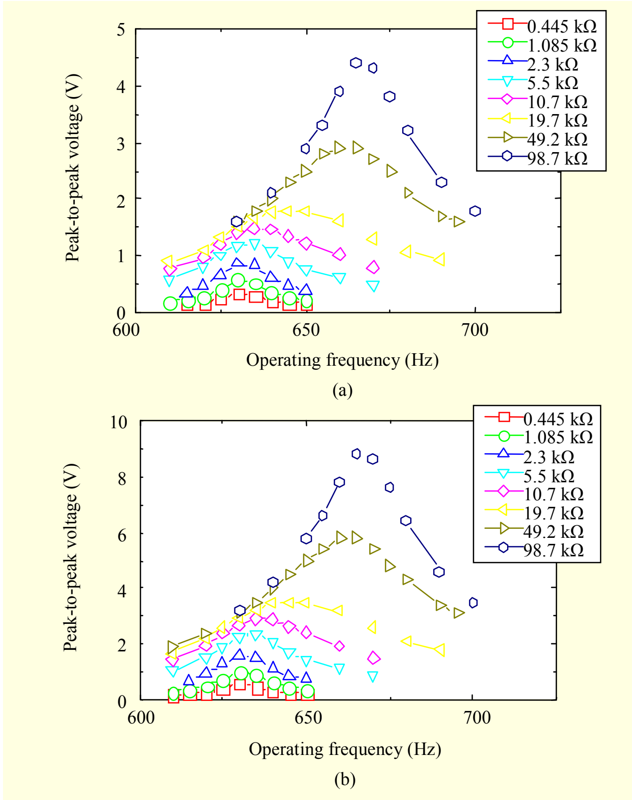

Fig. 4. Peak-to-peak output voltage versus frequency with varying resistive loads of the device for (a) 0.5 g_{rms} and (b) 1 g_{rms} acceleration.

connected resistive load. The peak-to-peak voltage versus frequency for the device is shown in Fig. 4. As in the generated AC voltage in the open circuit, the AC output voltage in the resistor shows a frequency-dependent symmetric distribution. A different point, the dispersion of peak-to-peak voltage with frequency, was also observed. The natural frequency of the device, f_r, can be described as $f_r = \frac{\pi}{2}\sqrt{\frac{K_{eff}}{M_{eff}}}$, where K_{eff} and M_{eff} are the effective spring constant and effective mass of a power-generating device, respectively. The M_{eff} value is a function of the device's mass, and K_{eff} is a function of piezoelectric material, such as $K_{eff} \propto K_{piezo} \times 1/(R_i+R_e)$, where R_i is the internal resistance of the piezoelectric material, and R_e is the resistance of the external resistor [24]. A variation of R_e may cause a modulation of the resonance frequency to a higher point as shown in the figure.

Figure 5 shows the calculated and measured output voltages and power as a function of resistive load at 0.5 g_{rms} and 1 g_{rms} accelerations, and a corresponding resonant frequency of 630 Hz.

The analytic expression for the output voltage and power of a cantilever-type piezoelectric energy-harvesting device can be easily found elsewhere [14], where the piezoelectric element is modeled as the AC voltage in-series with the capacitor [15]. Assuming that the frequency of the input vibrations is equal to the undamped natural frequency of the device, the calculated output voltage and power are well matched with the measured values as shown in Fig. 5.

The output voltage increases with an increasing resistive load and then becomes saturated upon further resistive loading. As an aside, the output power is at maximum at the optimized load resistor value. When the value of the resistive load is 2.3 kΩ, the maximum output power can be acquired, where electrical impedance matching occurs. The impedance Z of the piezoelectric cantilever device generating the maximum output power can be calculated as $Z = \frac{1}{2\pi f C}$, where f is the natural frequency of the cantilever, and C is the capacitance of the piezoelectric material [25]. Using this equation, the calculated impedance of the cantilever device is 3.2 kΩ, which is similar to the measured value.

Maximum output powers of about 0.08 mW and 0.28 mW were obtained with a 2.3 kΩ resistive load resulting in maximum power densities of about 1 mW/cm^3 and 3.5 mW/cm^3 for 0.5 g_{rms} and 1 g_{rms} accelerations, respectively.

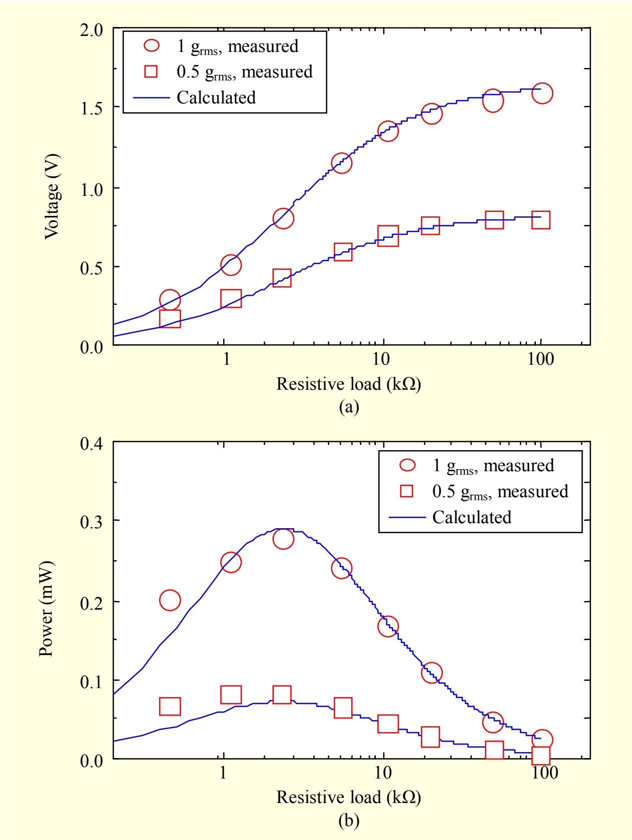

Fig. 5. Calculated and measured (a) output voltage and (b) output power as a function of resistive load at 0.5 g_{rms} and 1 g_{rms} accelerations at a resonant frequency of 630 Hz.

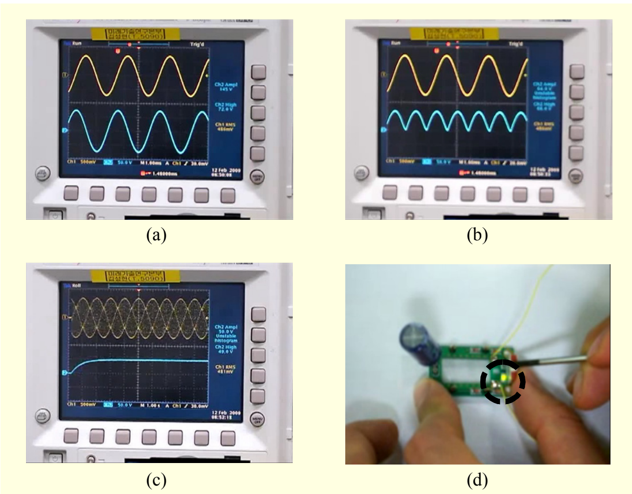

Fig. 6. Energy conversion and storage test results: (a) an applied vibration sine wave (upper line) and generated AC voltage (lower line), (b) rectified voltage (lower line), (c) charging curve in the capacitor of a digital oscilloscope (lower line), and (d) LED lightning using the charge in the capacitor.

The power density is calculated using the generated power divided by the effective volume of the device, which is much higher than the reported value [26]. It is believed that the Zr doping effects and large piezoelectric coupling factor of a [110]-poled crystal are the main factors of high power generation. The output power of the piezoelectric energy-harvesting device is increased with the acceleration applied in the device.

The energy conversion and storage test results are shown in Fig. 6. To short the charging time in the capacitor, the vibration is raised to 2 g_{rms} and the output power is 0.4 mW. The loss rate for the rectifying process is about 30%, and the magnitude of the capacitor was 1 μF. Therefore, the time needed for about an 86% charge is approximately 2 s. This means that our system has a time constant of 2 s in an RC circuit. The output power density after rectifying was about 1.3 mW/cm^3g_{rms}. This is quite high enough to implement a 15 mWh battery that can be charged in 2 h using 12 cantilever arrays. Note that a general thumb-sized button cell battery has a capacitance of 15 mWh. In this experiment, the LED lightning was possible using the charge in the capacitor as shown in Fig. 6(d).

It has been reported that common environmental vibrations such as those found in a building exhibit moderated amplitudes (< 1 g_{rms}) and lower frequencies, typically between 60 Hz and 200 Hz, and the requirements of continuous power for a typical bio-MEMS chip are 10 mW and 2.8 μW for an intermittent application (once per hour) [18]. For this goal, the proof mass of the cantilever structure is favorable to meet these conditions, not only to reduce the natural resonance frequency but also to generate a large amount of output power by inducing large strains for a given input vibration [26].

IV. Conclusion

We fabricated a piezoelectric energy-harvesting device using a Zr-doped PMN-PT piezoelectric single-crystal beam. The device generated a power of 0.28 mW and a power density of 3.5 mW/cm^3 with an optimal resistive load of about 2.3 kΩ from 1 g_{rms} acceleration at its resonant frequency of 630 Hz. The improved power is ascribed to the Zr-doping effects and the large piezoelectric coupling factor of [110]-poled piezoelectric crystal.

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References

[1] J.A. Stankovic, “When Sensor and Actuator Networks Cover the

World," *ETRI J.*, vol. 30, no. 5, 2008, pp. 627-33.
[2] S. Maeng et al., "SOI CMOS-Based Smart Gas Sensor System for Ubiquitous Sensor Networks," *ETRI J.*, vol. 30, no. 4, 2008, pp. 516-525.
[3] H.K. Lee et al., "Electroactive Polymer Actuator for Lens-Drive Unit in Auto-Focus Compact Camera Module," *ETRI J.*, vol. 31, no. 6, Dec. 2009, pp. 695-702.
[4] J.A. Paradiso and T. Starner, "Energy Scavenging for Mobile and Wireless Electronics," *IEEE Pervasice Comput.*, vol. 4, 2005, pp. 16-27.
[5] S. Roundy and P.K. Wright, "A Piezoelectric Vibration Based Generator for Wireless Electronics," *Smart Mater. Struct.*, vol. 13, 2004, pp. 1131-1142.
[6] S.R, Anton and H.A. Sodano, "A Review of Power Harvesting Using Piezoelectric Materials," *Smart Mater. Struct.*, vol. 16, 2007, pp. R1-21.
[7] J. Kim, "Formation of a Porous Silicon Anti-reflection Layer for a Silicon Solar Cell," *J. Korean Phys. Soc.*, vol. 50, 2007, pp. 1168-1171.
[8] S.P. Beeby, M.J. Tudor, and N.M. White, "Energy Harvesting Vibration Sources for Microsystems Applications," *Meas. Sci. Technol.*, vol. 17, 2006, pp. R175-195.
[9] M.Y. Kim, T.S. Oh, and J.S. Kim, "Annealing Behavior of Bi2Te3 Thermoelectric Semiconductor Electrodeposited for Nanowire Applications," *J. Korean Phys. Soc.*, vol. 50, 2007, pp. 670-676.
[10] Y.K. Hong and K.S. Moon, "Single Crystal Piezoelectric Transducers to Harvest Vibration Energy," *Proc. SPIE*, vol. 6048, 2005, pp. 60480E-1-3.
[11] A. Badel et al., "Single Crystals and Nonlinear Process for Outstanding Vibration-Powered Electrical Generators," *IEEE Trans. Ultrason., Ferroelectr., Freq. Control*, vol. 53, no. 4, 2006, pp. 673-684.
[12] S. Roundy, P.K. Wright, and J. Rabaey, "A Study of Low Level Vibrations as a Power Source for Wireless Sensor Nodes," *Comput. Commun.*, vol. 26, 2003, pp. 1131-1144.
[13] V.H. Schmidt, "Theoretical Electric Power Output per Unit Volume of PVF2 and Mechniacl-to-Electrical Conversion Efficiency as Functions of Frequency," *Proc. the 6th IEEE Int. Symp. Appl. Ferroelectr.*, 1986, pp. 538-542.
[14] J. Ajitsaria et al., "Modeling and Analysis of a Bimorph Piezoelectric Cantilever Beam for Voltage Generation," *Smart Mater. Struct.*, vol. 16, 2007, pp. 447-454.
[15] J.H. Cho et al., "Generated Power Characterization of Piezoelectrics with Electromechanical Coupling Coefficient and Quality Factor," *IEEE Ultrason. Symp.*, 2006, pp. 485-488.
[16] J. Twiefel et al., "Power Output Estimation and Experimental Validation for Piezoelectric Energy Harvesting Systems," *J. Electroceramics*, vol. 20, 2008, pp. 203-208.
[17] A. Erturk and D.J. Inman, "On Mechanical Modeling of Cantilevered Piezoelectric Vibration Energy Harvesters," *J. Intell. Mater. Syst. and Structures*, vol. 19, 2008, pp. 1311-1325.
[18] S. Priya, "Modeling of Electric Energy Harvesting Using Piezoelectric Windmill," *Appl. Phys. Lett.*, vol. 87, 2005, pp.184101-184103.
[19] Q. Chen and Q.M. Wang, "The Effective Electromechanical Coupling Coefficient of Piezoelectric Thin-Film Resonators," *Appl. Phys. Lett.*, vol. 86, 2005, pp. 022905-022906.
[20] H.W. Kim, S. Priya, and K. Uchino, "Modeling of Piezoelectric Energy Harvesting Using Cymbal Transducers," *Jpn. J. Appl. Phys.*, vol. 45, 2006, pp. 5836-5840.
[21] M. Renaud et al., "Piezoelectric Harvesters and MEMS Technology: Fabrication, Modeling and Measurements," *Proc. Transducers & Eurosensors*, 2007, pp. 891-894.
[22] http://www.ceracomp.com.
[23] J.W. Yi, W.Y. Shih, and W.H. Shih, "Effect of Length, Width, and Mode on the Mass Detection Sensitivity of Piezoelectric Unimorph Cantilevers," *J. Appl. Phys.*, vol. 91, 2003, pp. 1680-1686.
[24] S.J. Jeong et al., "Properties of a Multi-Stack Type Piezoelectric Energy Harvesting Device," *Integr. Ferroelectr.*, vol. 98, 2008, pp. 208-215.
[25] H.C. Song et al., "Multilayer Piezoelectric Energy Scavenger for Large Current Generation," *J. Electroceramics*, vol. 23, Oct. 2009, pp. 301-304.
[26] N.S. Hudak and G.G. Amatucci, "Small-Scale Energy Harvesting Through Thermoelectric, Vibration, and Radiofrequency Power Conversion," *J. Appl. Physics*, vol. 103, no. 10, 2008, pp. 101301-24.

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